

Physics for a Polarized Electron-Nucleon/Nucleus-Collider ^a

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A number of physics arguments for a high-luminosity high energy polarized Electron- Nucleon/Nucleus-Collider (i.e. with a luminosity of at least $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ and an invariant energy squared of at least $s \geq 100 \text{ GeV}^2$) are presented. The main purpose of this machine would be generally speaking the investigation of QCD beyond the twist-2 level respectively of nuclear physics beyond the level of 'effective' models. Specific topics are: twist-2 and twist-3 spin-asymmetries as probes of both the internal hadron structure and the hadronization process, Off-Forward-Parton-Distributions as a new dimension of QCD-physics, nuclear effects for the nucleon structure and nuclear effects for QCD-dynamics in nuclei. The last two topics are also of direct relevance for high-energy heavy-ion-collisions. We conclude that the need for such a collider is clear, if nuclear physics is to continue its development towards a comprehensive understanding of QCD phenomena.

1 Introduction

In recent years a marked development took place in which the hot topics of QCD moved more and more into the reach of the traditional nuclear physics community. This is illustrated most clearly by high-energy heavy-ion physics (RHIC and ALICE) but is also visible in the fact that many members of HERMES, COMPASS, the SLAC-spin-collaboration, and other similar collaborations have a nuclear physics background. Physicswise this development is fueled by the fact that most of the recent important progress in QCD concern higher-twist-effects, specific hadron-wavefunctions, low-energy limits of QCD, quasi-classical (Glauber-type) approximations for high-energy heavy-ion physics, ..., all of which expand the scope of QCD into the direction of more traditional nuclear physics. Consequently for the first time there is well-founded hope to finally be able to join both descriptions in a consistent manner. The main task for the next decade(s) as seen by many theoreticians and experimentalists is therefore to close the remaining gap in our understanding. Consequently, the discussions with respect to the most suitable machine for this purpose became rather lively in recent years. Of these ideas those which are closest to the spe-

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cific machine we are discussing here are: to add an electron-ring to RHIC, to more or less rebuildt CEBAF as a 25 GeV machine, to performe high luminosity experiments with an ELFE detector either at DESY or at CERN, etc. The main task is therefore to clarify, which physics questions favour which of these machines. In the following I shall address some of the relevant research topics, and shall trying to provide some (very partial) answers.

2 Higher-Twist versus Higher-Order-Perturbation-Theory

Many of the presently most hotly discussed issues in QCD focus on higher-twist-phenomena. To the extent that the understanding increases the meaning of this term in different contexts becomes, however, more and more specialised and thus ever more confusing to non-experts. Let me try to illustrate this with a few remarks which at the same time sketch the vast field of research for an EPIC-type collider. Originally 'higher-twist' was a rather general term for all processes suppressed by some hard scale, i.e. by powers of $1/Q^2$ for deep-inelastic scattering. This made sense in times when one was only aiming at finding some arguments to neglect these terms. By now one is primarily interested to understand their origin and such a broad definition is not really helpful. In a first step it is certainly useful to distinguish between 'power-corrections' like e.g. rather trivial finite-mass-corrections and terms which are due to correlators of more than two quark or gluon fields. The latter can, however, again be of different nature:

Higher-Twist in the framework of Operator-Product-Expansion

The term 'higher-twist' was originally defined within OPE. Here the moments of structure functions can be represented by specific local correlators of a certain number of fields within the hadron under investigation. A well known example is the third moment of the second spin structure function $g_2(x, Q^2)$, which is given by¹

$$\int_0^1 g_2^{p,n}(x, Q^2) x^2 dx = -\frac{1}{3}a_2 + \frac{1}{3}d_2 + \dots \quad (1)$$

$$d_2 \approx \langle PS | \bar{q} \gamma_\mu \tilde{G}_{\alpha\beta} \psi | PS \rangle \quad (2)$$

To distinguish higher twist from leading twist contributions by simply fitting the Q^2 dependence of structure functions requires very high statistics and a large kinematic domain (which in turn requires a sufficiently high s). This is so far only possible for the unpolarized case, see e.g.² and figure 1,

taken from that paper. The values plotted in this figure are the fitted $1/Q^2$ -corrections minus the target mass corrections

$$H_2(x) = \left(F_2^{\text{higher twist}}(x, Q^2) - F_2^{\text{target mass corrections}}(x, Q^2) \right) \frac{Q^2}{1 \text{ GeV}^2} \quad (3)$$

As the leading twist contribution to the third moment of g_2 is suppressed, it

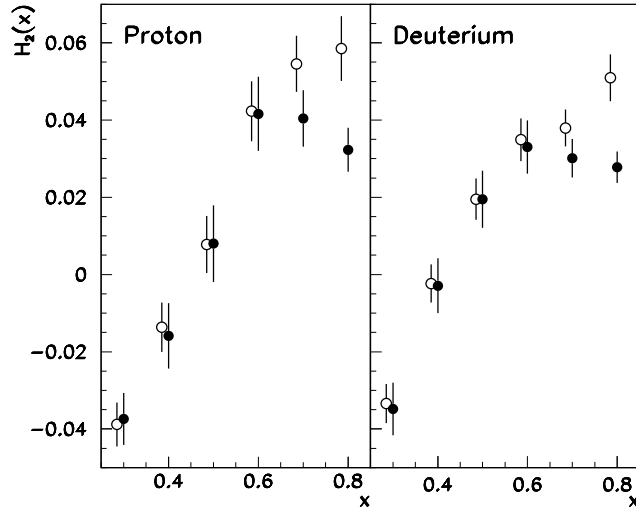


Figure 1: Genuine higher twist contributions as extracted from the presently available data on $F_2(x, Q^2)$. ($H_2(x) = \left(F_2^{\text{higher twist}}(x, Q^2) - F_2^{\text{target mass corrections}}(x, Q^2) \right) \frac{Q^2}{1 \text{ GeV}^2}$)

is also possible to extract d_2 from these data even for very limited statistics³. A far more precise determination will soon be published by E-155X. The determination of higher-twist-correlators from moments of structure functions does not only provide well defined information on the internal nucleon wave function which in turn allows to exclude many models and puts the different calculation techniques to a crucial test. In addition it also addresses a fundamental problem of quantum field theory in general. Perturbative expansions are only asymptotic series, i.e. they blow up at some order in α_s . This is illustrated in figure 2 for the perturbative corrections to Bjorken sum rule as calculated in 'Naive-Nonabelianization-Approximation', i.e. iterating only

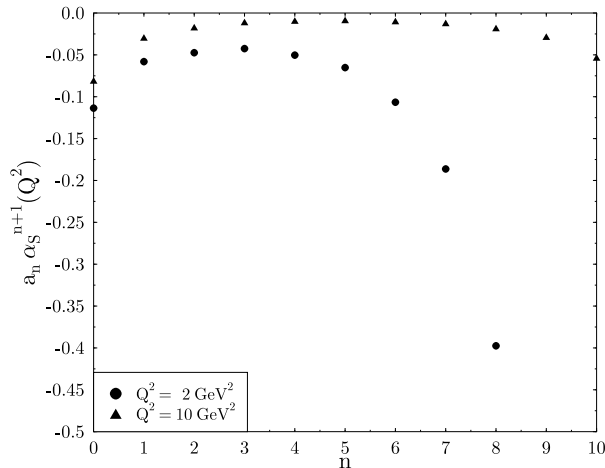


Figure 2: Perturbative corrections to Bjorken sum rule calculated in the Naive-Nonabelianization-Approximation, for two different values of Q^2 . The figure illustrates, that perturbative corrections define only an asymptotic series, that for medium large Q^2 they start to diverge already in rather low order, and that the convergence improves with increasing Q^2 .

those contributions contained in the leading order *beta*-function.

$$\int_0^1 dx (g_1^p(x) - g_1^n(x)) = \frac{g_A}{6g_V} \left(1 + \sum_{n=0}^{\infty} a_n \alpha_s^{n+1} \right) \quad (4)$$

Obviously the convergence of this series is rather bad for the typical Q^2 values of e.g. the SLAC and HERMES spin experiments. Only the sum of higher-twist corrections (better to be called power-corrections in this context) perturbative contributions and genuine non-perturbative (like e.g. instanton) contributions gives the physical result. The increase in the higher-order perturbative contributions is e.g. canceled by the power corrections⁴. The individual contributions are furthermore in general scheme dependent, somewhat comparable to the fact that in NLO the distribution functions in DIS become scheme dependent. For NLO (and NNLO etc.) calculations one has learned how to handle this, for the power corrections a full understanding still has to be developed. Let us note as an illustration, that the perturbative corrections plus the renormalon-power-corrections as calculated in the \overline{MS} scheme can be reex-

pressed as just the first order perturbative corrections with a suitable redefined scale-parameter (BLM-scheme)⁵. To understand these fascinating fundamental aspects of quantum field theory in depth one really needs precisely measured Q^2 -dependences of as many moments of structure functions as possible.

Higher-twist in semi-inclusive reactions

The investigation of semi-inclusive reactions of the type

$$e + p \rightarrow e' + h_1 (+h_2) + X \quad (5)$$

plays already a major role for the ongoing experiments and will do much more so for all planned ones. The theoretical analyses of these reactions is very involved and combines leading and higher twist distribution and fragmentation functions. Reactions of the type (3) are already presently used for many applications. Let me give just a very few examples. From pion production in polarized lepton-nucleon collisions HERMES and SMC gained information on the flavour decomposition of the nucleon spin, which is independent from those information contained in the inclusive structure functions. HERMES was even able to obtain a first direct glimpse of the polarized gluon distribution, which will be investigated in far more detail by COMPASS, e.g. by using open charm production. Also charm and strangeness production in unpolarized collisions is of great interest, as it helps to clarify how much strange and charm quarks there are in a nucleon. Recent HERA data strongly suggests that there could e.g. be substantial intrinsic charm in the nucleon (see the talks by T. Adams and R. Vogt). There are actually by now so much data and so many theoretical aspects to this kind of reactions, that it is not possible to review it in any reasonable manner here. Some more information is given in the talks by Melnitchouk, Radici, Carlson and de Florian.

It turned out that this type of reactions is full of surprises, such that there is a constant need for improved experimental data (for larger kinematic regions and with higher statistics). As an example let me mention that HERMES recently observed for the first time a specific azimuthal single spin asymmetry which can be related to well defined combinations of up to now completely unknown distribution and fragmentation functions. For detailed discussion of the complicated situation arising from the inclusion of spin please see the talk by Piet Mulders. It seems save to conclude that semi-inclusive and (exclusive) reactions will play the most important role for any future project on lepton-nucleon/nucleus scattering. A collider geometry and kinematics is extremely helpful for such studies, as it makes also the target fragmentation region fully accessible.

Higher-twist wave-functions and exclusive reactions

Also totally exclusive reactions at high Q^2 gain more and more interest. The task here is to pin down the hadron-wave functions (i.e. the lightcone wave-functions) with increasing precision. This leads to an expansion which can be thought of as a kind of Fock-state expansion in a specific kinematics. For the

ρ meson the quantities of interest are e.g. of the type⁶

$$\langle 0 | \bar{u}(z) i g \tilde{G}_{\mu\nu}(vz) d(-z) | \rho^-(P, \lambda) \rangle \quad (6)$$

Expansions keeping the higher order terms which contain more than the minimum number of fields are called higher-twist distribution amplitudes. Again the meaning of the term is slightly different in this context. A large fraction of the experiments to be done at an EPIC-type machine will address this type of higher-twist contributions. It should also be noted that heavy quark physics, which will gain substantially in importance over the next years should accelerate the development in this field. Many hadron decays involving heavy quarks can be analysed in terms of such higher-twist distribution amplitudes. Their detailed experimental investigation will catalyze their improved theoretical description (and vice versa). One can therefore foresee that by the time an EPIC type machine would start operating a large number of observables will have a very well defined significance in terms of clearly defined QCD amplitudes. On the other hand the expected progress will lead to substantial demand for complementary experiments. As for this type of physics luminosity is more important than high energy, it is, however, not obvious that an EPIC type machine would be better suited than an ELFE type one.

Higher-Twist Evolution and saturation in heavy ions

One of the crucial questions for high-energy heavy-ion-collisions and small- x physics as investigated e.g. by HERA is the appearance of non-linear effects in the Q^2 -evolution equations at very small x . These are driven by the gluon distribution functions becoming large and should at the latest be relevant if $\alpha_s G(x, Q^2)$ becomes larger than one. It seems that HERA is just able to touch this region. For nuclei these non-linear effects should set in much earlier as the soft gluons becomes delocalized within the line of sight within a nucleus, leading to an $A^{1/3}$ enhancement factor. As $G(x, Q^2)$ is given by the square of a gluon-field operator with dimension (energy)² these non-linear terms are typically suppressed by a factor $1/Q^2$. For a specific example see e.g.⁷ where the conclusion is reached that in heavy nuclei the quark and gluon distributions behave like

$$\begin{aligned} \frac{d(xq(x))}{d^2 b d^2 l} &= \frac{N_c}{6\pi^4} \frac{Q_s^2}{l^2} & \text{for} & \quad l^2 \gg Q_s^2 \\ &= \frac{N_c}{2\pi^4} & \text{for} & \quad l^2 \ll Q_s^2 \end{aligned} \quad (7)$$

$$\begin{aligned} \frac{d(xG(x))}{d^2 b d^2 l} &= \frac{N_c^2 - 1}{4\pi^4} \frac{Q_s^2}{l^2} \ln(1/x) & \text{for} & \quad l^2 \gg Q_s^2 \\ &= \frac{N_c^2 - 1}{4\pi^4} \ln(1/x) & \text{for} & \quad l^2 \ll Q_s^2 \end{aligned} \quad , \quad (8)$$

i.e. the parton distributions are suppressed by a factor $1/Q^2$ when the transverse momentum of the outgoing quark l is small compared to some saturation momentum Q_s . b is the impact parameter of the collision. This problem has been approached along many different lines, some of which seem to be more or less equivalent in comparable semi-classical approximations⁸. The characteristic property shared by all of them is that for very small- x a saturation of the gluon density is suggested. There is even some experimental evidence for such a saturation process in recent HERA data⁹. Figure 3 shows $dF_2/d\log(Q^2)$,

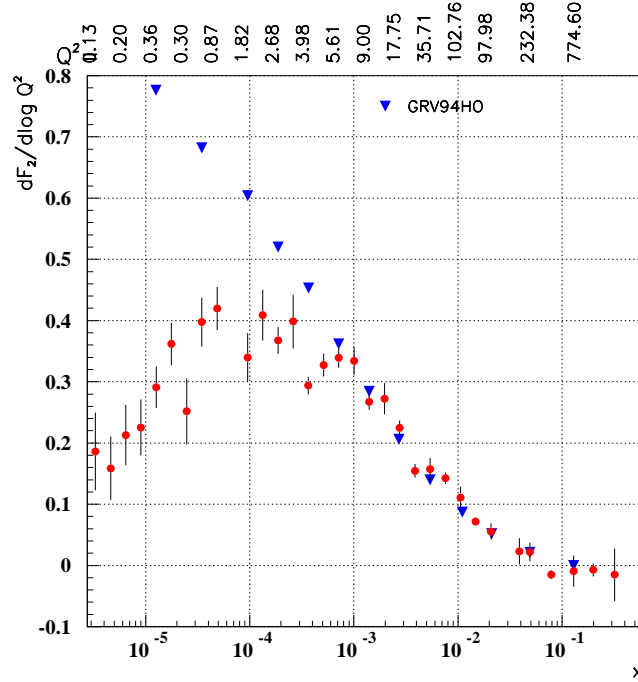


Figure 3: The Caldwell plot for recent HERA data. The logarithmic derivative $dF_2/d\log(Q^2)$ should be proportional to $xG(x, Q^2)$.

a quantity which should in leading order be proportional to the gluon distribution function $xG(x, Q^2)$, as a function of x . The marked decrease below $x = 10^{-4}$ is taken as evidence for saturation. To investigate this specific kind of higher-twist effects in nuclei one would like to have, however, more energy than envisaged for EPIC. Assuming that the nuclear effects compensate about one to two orders of magnitude in x one finds that with $s = 1000 \text{ GeV}^2$ one

could reach a domain comparable to HERA and thus start to see saturation effects (just as in figure 3). An electron ring at RHIC or heavy ions in HERA are probably the better options for this kind of physics.

3 Off-Forward-Parton-Distributions (OFPD)

The factorization proof for diffractive meson production¹⁰ opened a large class of semi-inclusive observables to stringent QCD analyses¹¹. The OFPDs (or skewed parton distributions etc.) provide a new type of specific information on hadronic wavefunctions. They are of special importance in connection with internal orbital angular momentum of e.g. the quarks and gluons in a nucleon¹². It even seems as if it must be possible to formulate any observable sensitive to these internal angular momenta in terms of OFPDs. With planned experiments aiming at a determination of the spin-polarized gluon distribution $\Delta G(x, Q^2)$ one of the main aims of future spin physics experiments will be to determine the still remaining quantities in the total angular momentum sum of the nucleon, namely the orbital angular momentum contributions. Much theoretical work is still needed to understand their status better. As an example figure 4 shows a typical example for the result of Q^2 -evolution for the angular momentum distributions as defined by us¹³. We find that the large $\Delta G(x)$ generated by Q^2 -evolution in NLO is mainly balanced by $L_G(x)$. While it seems obvious that many observables should depend on it, it was not possible so far to derive in a formally clean manner a precise relation between any observable and the specific correlators associated with orbital angular momentum. The situation is very tricky as the way in which calculations are currently done one has to fix a specific gauge and factorization scheme. It is controversial whether a gauge independent formulation can be found. It might be that the value of those correlators which correspond to our naive understanding of orbital angular momentum depend on the gauge considered. This would not be a principle problem (the singlet quark spin $\Delta\Sigma$ depends e.g. also on the chosen factorization scheme), it just needs carefully continued studies.

One problem of OFPDs which is basically solved concerns their Q^2 -evolution. By now there do exist running LO and NLO codes both for the singlet and non-singlet channel. Figure 5 shows a typical example for the results of LO- and NLO- Q^2 -evolution. The main message of this figure is that the differences between NLO and LO are not large, such that one can expect that also the effect of all higher orders is small. Studies of the evolution effects should help to identify those OFPD-models which are relatively stable under evolution and thus physically acceptable.

Another major theoretical problems are to extend the validity of the factoriza-

tion proofs to a wider class of reactions, which should be possible. Also here the work is ongoing. Finally, there is the question what these proofs imply in praxis. Basically, they show that the leading contributions in $1/Q^2$ can be parametrized by twist-2 OFPDs. For practical experiments it is, however, crucial to know the proportionality factor in front of the $1/Q^2$ -power-corrections as it determines how large Q^2 has to be such that the higher-twist terms become really negligible. This is basically still unknown, but first rough estimates give hints that these factors are disquietingly large¹⁵. Experimentally, this implies that for the measurement of OFPDs one needs a large kinematic region, high statistics and the possibility to measure in a clean way the final state hadrons. Meeting these three requirements is basically the definition of an EPIC-type machine. The investigation of OFPDs should therefore become a major issue in its program. This topic is covered in far more detail in the contribution by Mark Strikman.

4 Nuclear Effects

Diffraction reactions similar to those just discussed for the case of OFPDs play also a major role for e+A collisions. First of all their cross-sections are sizeable. In the limit of a completely black disc, quantum mechanics implies that it is half of the total cross section. For the values of the invariant energy-squared s we are considering, a nucleus is not a black disc, but estimates suggest that diffractive cross sections are comparable in size to usual ones. The next point is that there is an intimate connection between shadowing and diffraction. Gribov theory unambiguously relates e.g. diffractive processes in the scattering of a projectile off a single nucleon to nuclear shadowing due to the interaction of the projectile with two nucleons. Also one should keep in mind that while it is customary to discuss all nuclear effects in terms of shadowing and anti-shadowing the underlying microscopic interaction mechanisms are rather varied and there are many additional detailed questions to be answered. As an example figure 6 shows the dependence of the nuclear transparency T_A on the coherence length l_c as recently measured by HERMES. One definitely would like to study this effect as a function of Q^2 up to values in which purely perturbative processes take over, which would require, however, much higher energy. This high energy is generally needed to connect smoothly reactions taking place primarily within a nucleus with those taking mainly place outside of it.

A question of general concern is how large higher-twist effects in nuclei are in general and whether perturbative QCD still makes sense for reactions tak-

ing place inside of nuclei. The main issue here are effects due to the strong, delocalized soft gluonfields in nuclei. Thus the discussion is related to that of gluon saturation in nuclei. A powerful approach to deal with this problem was developed by Sterman and collaborators^{18,19} (which is too involved to be discussed here in detail). The paper by Guo¹⁹ illustrate very nicely that the effects are potentially of order 100 percent. Clearly this issue requires more intensive theoretical and experimental studies.

5 Conclusions

I have briefly sketched some questions to be addressed by an EPIC-type collider. The basic aim of such a machine would be to explore the **internal structure of hadrons** beyond simple twist-2 distribution functions in an infinite momentum frame (when seen from the high-energy perspective) and beyond 'effective models' (when seen from the traditional nuclear physics perspective). The second important aim would be to understand better the **QCD dynamics** of reactions taking place in nuclei. Keeping in mind that there was tremendous theoretical progress in both fields during the last few years it is clear that with improved understanding more and more observables will become accessible to a detailed interpretation. Extrapolating the current development, it is therefore obvious that in a few years from now a still much larger collection of interesting clearly interpretable semi-inclusive and exclusive electron-nucleon/nucleus reactions would wait to be investigated experimentally. Basically all of these would require, however, an EPIC-type machine.

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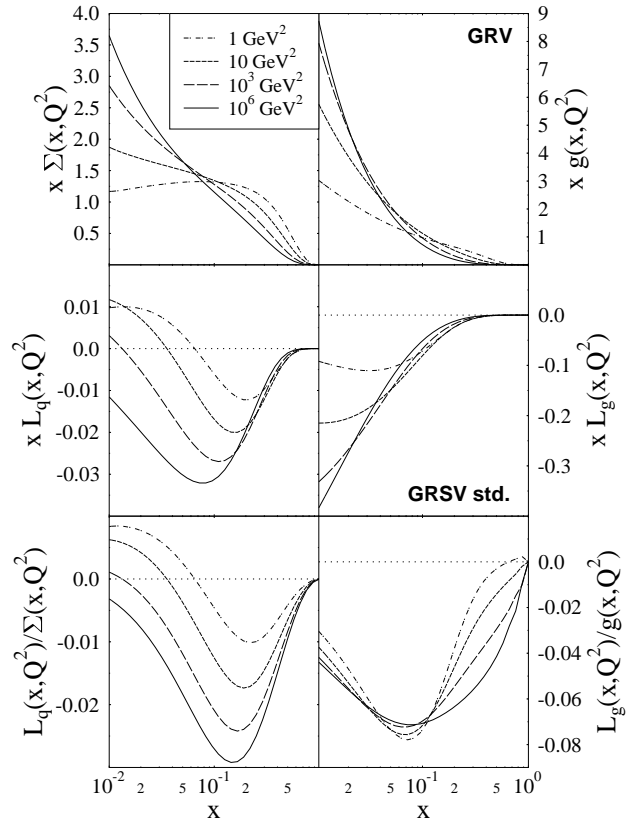


Figure 4: Result of Q^2 -evolution for the GRV leading order standard scenario with $\mu_0^2 = 0.23 \text{ GeV}^2$

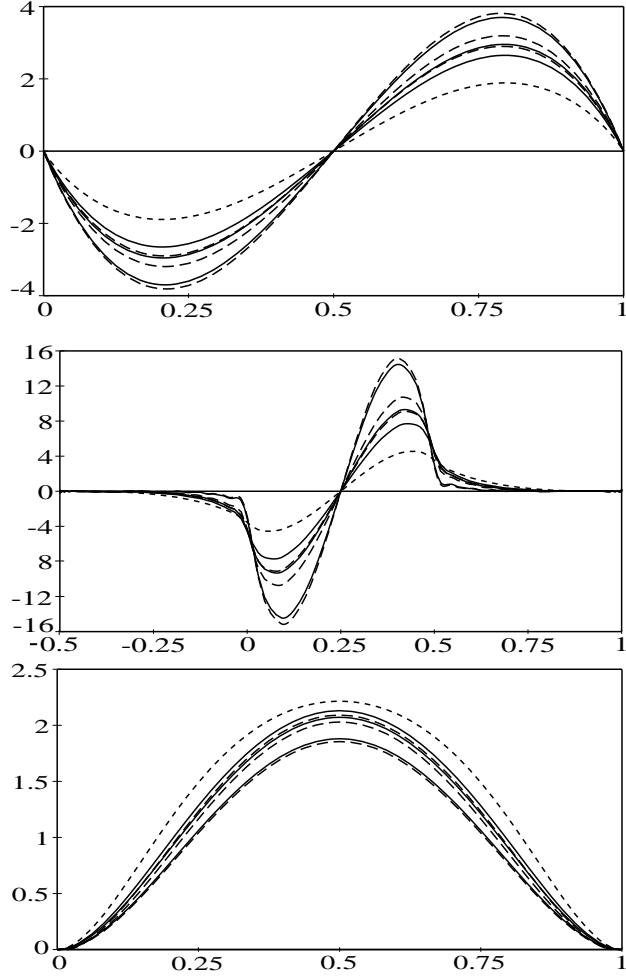


Figure 5: Evolution of the non-forward singlet quark distributions $\mathcal{Q}(x, \zeta)$. The input function at $Q_0 = 0.7$ GeV is shown by the short-dashed line at different ζ 's. The full curves moving away from the initial function correspond to LO results for $Q^2 = 10, 10^2, 10^{14}$ GeV², respectively. The long-dashed lines give the NLO results for the same values of the momentum scale in the same order.

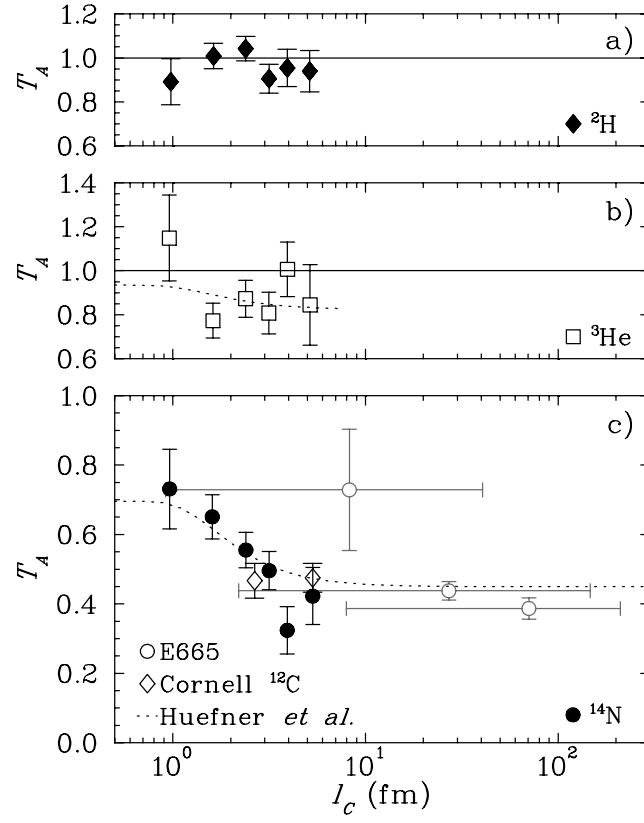


Figure 6: Dependence of the nuclear transparency $T_A = \sigma_A/(A\sigma_H)$ as a function of the coherence length $l_c = 2\nu/(Q^2 + M_{q+\bar{q}}^2)$. The dashed curve is the theoretical prediction .